Introduction to Lightning Detection

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Complete List of Authors:	Fullekrug, Martin; University of Bath, Electronic and Electrical Engineering
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Introduction to Lightning Detection

Martin Fullekrug
University of Bath, Centre for Space, Atmospheric and Oceanic Science, Dept. of Electronic and Electrical Engineering
Claverton Down, Bath, BA2 7AY

Corresponding Author: eesmf@bath.ac.uk
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Abstract. Lightning discharges are composed of numerous different physical processes. The spectrum of these lightning discharge processes ranges from quasi-static electromagnetic fields ~1-4 Hz to micro- waves and from optical wavelengths up to gamma rays with energies ~40-100 MeV. This multi-scale nature of lightning discharges is impossible to measure in its entirety with nowadays technology. As a result, a specific physical process of the lightning discharge needs to be chosen for a given application. This choice determines the spectral range and the corresponding measurement technology for lightning detection. The most recent developments in lightning detection are discussed and promising areas of future research with a potential for novel discoveries are proposed.

Introduction. This brief overview on lightning detection is largely based on two extensive monographs on the physics of thunderstorms (McGorman and Rust, 1998) and lightning discharges (Rakov and Uman, 2003).

Thundercloud charge. Convection lifts air parcels beyond the condensation level where cloud droplets, ice crystals and graupel form. In the mixed phase region near ~4-6 km height, super-cooled water droplets, ice crystals and riming graupel co-exist such that the collisions between ice crystals and riming graupel result in the separation of electrical charges (Pereyra et al., 2000, Saunders et al., 1991). The negative charges are carried by graupel which remains in the mixed phase region as a result of gravitational forces, while the ice crystals with positive charges are carried aloft by the updrafts to form part of the thundercloud anvil. The thundercloud thereby develops a quasi-static electric field configuration with a complexity that scales with the size of the thundercloud (Krehbiel et al., 2008, Stolzenburg et al., 1998). When the potential difference between a negative and positive charge reservoir inside the thundercloud exceeds the breakdown electric field ~3 MV/m between ice crystals (Rison et al., 2016), the air becomes suddenly conductive and dielectric breakdown occurs. The neutralisation of the two charge reservoirs results in a sudden change of the quasi-static electric field configuration inside the thundercloud that can be measured with electric field mills (Koshak and Kreider, 1989) and quasi-static current detectors (Bennett and Harrison, 2013, Bennett, 2013).

Streamer. The reduction of a local electric field inside the thundercloud and the conversion of electrostatic energy to optical is known as a discharge process. This discharge process starts as a small scale streamer discharge that is commonly believed to initiate from the irregular surface of hydrometeors (Rison et al., 2016, Keith and Saunders, 1988), possibly as a result of relativistic runaway breakdown caused by extensive atmospheric (cosmic ray) showers (Gurevich and Karashtin, 2013, Gurevich et al., 2005, Marshall et al., 1995). Streamer discharges are measured by use of radio frequency (RF) microwaves in the frequency range ~0.4-1 GHz (Petersen and Beasley, 2014, Brook and Kitagawa, 1964).

Leader. The streamer discharge eventually grows into a leader discharge during a streamer-to-leader transition that remains to be described in detail. The leader discharge progresses in discrete steps (Pasko, 2014) with a height dependent length on the order of tens of meters. Each of these leader steps has a typical duration ~1-2 μs and emits electromagnetic radiation in the frequency range ~60-200 MHz (Rison et al., 2016, Mazur et al., 1997). Numerous consecutive and concatenating leader steps inside the cloud are collectively named intra-cloud (IC) discharge. About ~90% of all lightning discharges are IC discharges. Upward propagating leader discharges develop high electric fields at the leader tip which can accelerate electrons to relativistic energies and cause terrestrial gamma ray flashes (Celestin and Pasko, 2011, Stanley et al., 2006). The gamma rays can reach energies ~10-100 MeV as observed from Low-Earth Orbit (LEO) satellites (Tavani et al., 2011, Smith et al., 2005, Fishman et al., 1994) and aircraft (Kochkin et al., 2015, Dwyer et al., 2010). X-rays have been observed in association with rocket triggered stepped leaders and inside thunderclouds (Dwyer et al., 2003, McCarthy and Parks, 1985). The knowledge on ionizing radiation associated with lightning discharges is currently rapidly increasing (Dwyer and Uman, 2014). IC discharges are perceived as sheet lightning when observed over long distances at vantage points on the ground. If the distances exceed ~100 km or more, sheet lightning is most commonly perceived to be orange, but red, blue and green tints can also be observed, depending on the complexity of the light scatter inside the thundercloud and the scatter during the propagation of the light through the atmosphere (Figure 1).

Figure 1. Lightning discharges appear in various colours depending on the scatter of light inside the thundercloud and in the atmosphere. The intra cloud lightning discharges in the centre of the thundercloud appear to be white with a bluish tint and the cloud to ground discharge below appears to be orange. The right hand side of the thundercloud exhibits a green tint that is attributed to the unique composition of hydrometeors inside the thundercloud. The photo was taken in the late evening of Tuesday, September 10th, 2013, near Tarragona in north-eastern Spain. The exposure was 10 seconds f/2.8 ISO 400 with Tamron 90 mm on Canon EOS 5D (courtesy of Oscar van der Velde, http://www.lightningwizard.com/index.php?type=sets&setId=72157624159585244&page=2, accessed June 10th, 2016).

Return stroke. When a stepped leader approaches the ground, the enhanced electric field at the top of elevated structures can generate an upward propagating leader that attaches to the downward propagating leader. This attachment process results in a conductive channel between the thundercloud and the ground named return stroke. The return stroke has a duration ~60-80 μs and emits broadband electromagnetic radiation with a spectral maximum ~5-15 kHz. The return stroke is the most powerful process of a lightning discharge to reduce the electric field caused by the thundercloud. Consecutive discharges in the existing conductive channel are named strokes. On average, three strokes occur with time delays on the order of tens of milliseconds between them such that these consecutive strokes are perceived as a flickering luminosity of the lightning discharge.

Continuing current. After the last return stroke, it is possible that a lightning continuing current occurs (Kitagawa et al., 1962, Brook et al., 1962). The continuous flow of current in the existing conductive channel can be sustained, for example, by a horizontally extending leader progression that supplies the continuing current with charge from scattered charge reservoirs inside the thundercloud. The continuing current has a duration >40 ms and it emits narrow band electromagnetic radiation from ~1-4 Hz up to ~1 kHz. The continuing current results in a large charge transfer as a result of the relatively long integration time of the continuing current inferred from impedance measurements (Burke and Jones, 1992). The current waveform of the discharge process can also be inferred from the measurements by an inversion that takes into account the electromagnetic wave propagation from the source to the receiver (Mlynarczyk et al., 2015, Füllekrug et al., 2006, Cummer et al., 1998).

Cloud to ground discharge. The downward propagating leader steps, the return stroke, and the eventual consecutive strokes and continuing current are collectively named cloud to ground (CG) discharge. About ~90% of all CG discharges transport a net negative charge to the ground. The transport of electrons with an average total charge of ~20 Coulombs in the lightning channel with a diameter ~1-3 cm causes a substantial heating of the air molecules up to temperatures ~20,000-30,000 K. The rapidly expanding air emanating from the plasma channel results in a shock wave that is perceived at distances up to ~20 km as audible thunder (Johnson et al., 2011, Teer and Few, 1974). Nearby CG discharges generate thunder with a sound similar to claps such that the discharge can be imaged with an acoustic camera (Dayeh, et al., 2015). Acoustic cameras were originally developed to study the vibrations of car and aircraft chassis. The sound waves from distant lightning discharges exhibit significant dispersion and scatter from topographic features which results in a deep rumbling sound that extends from the audible down to the infrasound <20 Hz (Farges and Blanc, 2010). The relaxation of the plasma channel results in the emission of photons which are perceived as a flash of light that can be recorded with photo, video and film cameras, fast scanning diodes and photometers, spectrographs and other specialised optical recording equipment. The total duration of a CG discharge is ~100-200 ms with an estimated 100% duty cycle for electromagnetic radiation (Ngin et al., 2013, Mazur et al., 1997)

Limitations. Lightning discharge processes can be detected by measuring quasi-electrostatic signals, radio waves in various frequency ranges, optical signals, gamma ray flashes and sound waves. However, any real world measurement technology has limited capabilities such that the number of all lightning processes N_{LP} needs to be inferred from the number of detected events N_D, the detection efficiency DE and false alarm rate FA of the instrument and its spatial S_e and temporal T_e effectiveness such that

$$N_{LP} = N_D \frac{1 - FA}{DE} S_e T_e$$

(Ignaccolo et al., 2006). For example, the capability of an instrument to detect a lightning discharge process, i.e., the detection efficiency, often depends on the intensity of the source, the distance between the source and the instrument, the absorption along the propagation path, and the sensitivity of the instrument used for detection. The false alarm rate is often limited by the ability of the instrument to discriminate between competing natural processes and by the interference from unwanted signals of unknown origin. As a result, only two measurement technologies are most commonly used to locate lightning discharges, radio waves and optical signals.

Optical. Optical observations of lightning discharge processes on the ground are limited by the visibility at a given location which is mainly determined by the local cloud cover and permanent obstructions. As a result, optical observations from the vantage point of space offer the best representation of lightning activity with the added benefit of the ability to map lightning activity around the entire globe (Christian et al., 2003, Goodman and Christian, 1993). Optical sensors use an oxygen emission line at 777.4 nm to observe lightning discharge processes because this optical emission can be detected during day and night time (Figure 2). Satellite observations of lightning discharges are justified by the forecasting and now-casting of severe weather associated with thunderstorms such as hail, flash floods and gusty winds which tend to produce significant damage and are a threat to living beings, similar to lightning discharges. Future optical observations of lightning activity will be conducted from geostationary orbit with the GOES-R and MTG spacecraft (Goodman et al., 2013).

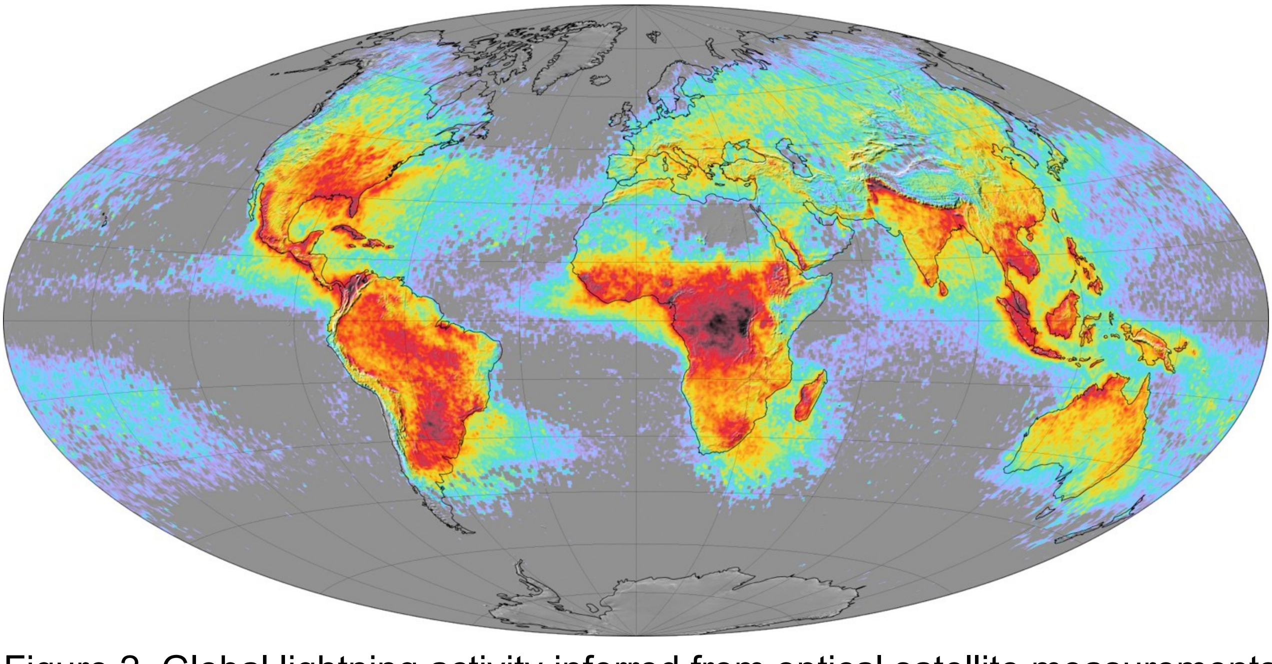

Figure 2. Global lightning activity inferred from optical satellite measurements. The lightning flash densities range from ~0.1-0.4 per km^2 per year (light purple/cyan) to ~30-70 per km^2 per year (red/black) as inferred from the Optical Transient Detector (OTD) and Lightning Imaging Sensor (LIS) on board of NASA spacecraft in the years 1995-2002 (NASA image prepared by Marit Jentoft-Nilsen, based on data provided by the Global Hydrology and Climate Center Lightning Team, http://earthobservatory.nasa.gov/IOTD/view.php?id=6679, accessed June 10th, 2016).

Radio Waves. The most commonly used radio remote sensing technologies to detect lightning discharge processes are measurements in the frequency range ~60-200 MHz to observe stepped leaders (Rison et al., 2016), ~1-400 kHz to observe return strokes (Cummins et al., 1998), and ~4-1,000 Hz to observe lightning continuing current (Cummer et al., 2013). It is common practice to measure the vertical electric field and/or the horizontal magnetic field because the horizontal electric field and vertical magnetic field include additional contributions from the electromagnetic fields of the induced currents inside the conductive Earth.

Horizontal magnetic field measurements are used for the magnetic direction finding (MDF) of lightning discharges. The horizontal magnetic field can be measured with a pair of air-loop coils or induction coils, both of which are band limited as a result of their finite capacitance. The magnetic direction finding method is based on the observation of transverse electromagnetic waves where the magnetic field vector is perpendicular to the direction of propagation aligned with the energy flux described by the Poynting vector of the electromagnetic wave. The horizontal magnetic fields can be displayed in the north-south and east-west directions, i.e., a hodogram, that can be used to determine the arrival direction of an electromagnetic wave with a 180 deg. ambiguity such that a network of radio receivers is needed to resolve this ambiguity. Magnetic direction finding can exhibit significant site errors that depend on the local geology and require an empirical correction (Bor et al., 2016, Füllekrug and Sukhorukov, 1999). As a result, magnetic direction finding has become less popular since the the wide spread availability of atomic time distributed by Global Navigation Satellite Systems (GNSS) such as GPS.

The disruptive GNSS technology made it more economic to operate networks of radio receivers which record the vertical electric field with an electric monopole antenna, dipole antenna, whip antenna or a capacitive probe. The occurrence time of a specific feature of the electric field waveform is measured to determine the time of arrival differences between pairs of radio receivers. The source location of the lightning discharge is then found at the best possible intersection of the hyperbolas with constant time, or distance, differences to determine a lightning discharge location with high precision. This methodology is now routinely used for the detection of stepped leaders in three dimensions (Rison et al., 2016) and return strokes on the continental and global scale (Said et al., 2013, Dowden et al., 2002).

Rapid advances in the ability of radio receivers to store large quantities of the originally recorded data allied by a significant increase of digital signal processing capabilities result in the recent development of various interferometric methods for the detection of lightning discharge processes (Stock et al., 2014) and radio waves (Füllekrug et al., 2014). The generic wording 'interferometry' is used for a variety of methods that are based on the timing of radio receiver networks, including time of arrival difference analysis, the cross correlation of impulsive signals, and a determination of the instantaneous phase for more continuous lightning discharge signals (Füllekrug et al., 2015, Lyu et al., 2014, Stock et al., 2014, Mazur et al., 1997).

Summary. The multi-scale nature of lightning discharges offers numerous opportunities for lightning detection. As a result, it is the specific application that determines the choice of a physical discharge process with a corresponding measurement technology to achieve the aim of the application associated with lightning detection. Potential for future research includes radio interferometry with receiver networks in all frequency ranges, the detection of streamers and their transition to leaders, ionizing radiation associated with lightning discharges, and the innovation opportunities arising from optical lightning detection on the forthcoming geostationary spacecraft.

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